

Continental shelf zones influenced by the suspended matter flows coming from Cadiz Bay

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ABSTRACT

Due to the diversity of environments and hydrodynamics in Cadiz Bay, it is of interest to study the dynamics of sedimentary exchange between the coastal zones and continental shelf. The most abundant clay minerals on the floor of the continental shelf and Cadiz Bay, and in the particulate matter in suspension, are: illite, smectite, kaolinite + chlorite, and the interstratified clay minerals illite-smectite. The average concentration of suspended matter is 6.5 mg/l, the lowest (1.37 mg/l) being found on the inner shelf and in the inner zones of the bay less affected by currents and surge. The highest values (14 mg/l) are found in the outer bay, consistent with the distribution of muddy facies on the sea floor.

The flow paths have been established from the local variations in the mineralogical associations found at the sampling stations, and by means of the alignments of the lowest values of the factor loadings at those stations most affected by the flows. The mineralogical similarity of the components of the clay fraction is related to the mixing action undergone by the components of the suspended matter reaching the bay from various sources, probably produced by the continuous action of the tidal ebb currents flowing from the inner sectors of the bay towards the continental shelf.

Key words: Continental shelf, sedimentary exchange, suspended matter, clay minerals.

RESUMEN

Zonas de la plataforma continental afectadas por los flujos de materia en suspensión procedentes de la bahía de Cádiz

El estudio de la dinámica de intercambio sedimentario entre las zonas litorales y la plataforma continental es de gran interés en el caso de la bahía de Cádiz, debido a su diversidad de ambientes y situaciones hidrodinámicas. Los minerales de la arcilla más abundantes en los fondos de la plataforma y la bahía, y en la materia en suspensión, son illita, esmectita, caolinita + clorita e interestratificados illita-esmectita. La concentración de materia sólida en suspensión indica un contenido promedio de 6,5 mg/l, apareciendo los mínimos (1,37 mg/l) en la plataforma interna y en zonas internas de la bahía no afectadas por corrientes y oleaje. Los valores más altos se dan en la bahía externa (14 mg/l), de acuerdo con la distribución de facies fangosas en el fondo.

Las trayectorias de los flujos salientes se han establecido a partir de las variaciones locales de las asociaciones mineralógicas en las diferentes estaciones de muestreo, alineándose los valores más bajos de los factores en las estaciones más afectadas por la acción de los flujos. La similitud mineralógica de los componentes de

la fracción arcilla en todos los ambientes se debe a la mezcla de componentes de la materia en suspensión que, desde diferentes fuentes, llegan a la bahía, y es favorecida por la acción de la corriente de refluo mareaal desde el sector más interno de la bahía a la plataforma continental.

Palabras clave: Plataforma continental, intercambio sedimentario, materia en suspensión, minerales de arcilla.

INTRODUCTION

In Cadiz Bay (southwest Spain), the study of the dynamics of sedimentary exchange between the coastal zones and the continental shelf is complex, and presents difficulties due both to the diversity of processes and environments, and to the possibility of hydrodynamic factors related to the climate of the zone and the physiography of the coast and sea floor. Furthermore, relatively little is known about the area, because of the lack of criteria for differentiating sea-floor sediments and matter in suspension.

Although the sources contributing sediments to Cadiz Bay and to the adjacent continental shelf have already been generally established (Mabesoone, 1963; Heezen and Johnson, 1969; Mélières, 1974; Grousset *et al.*, 1988; Gutiérrez Mas *et al.*, 1995; Moral Cardona *et al.*, 1996; Gutiérrez Mas *et al.*, 1997), the paths by which sediment is transported from the different source areas are still not well known. The lack of a sufficiently comprehensive hydrodynamic model to date therefore requires the study of natural tracers, and sophisticated statistical analysis to establish the paths followed by the particles, complemented by relevant environmental knowledge.

The minerals of the clay fraction have been used as tracers, since their small size makes them the only particles susceptible of being transported away from the bay, out towards the continental shelf. The present study, using tracers, has been complemented by sedimentological data, satellite images and other available information.

Characteristics of the study zone

From their sedimentological characteristics, Cadiz Bay and the adjacent continental shelf constitute an example of a siliciclastic sedimentary marine environment of middle latitude. The influence of the hydrodynamic system, sea-level changes, tec-

tonic structure and morphology of the coast and the continental margin, are reflected in the variety and distribution of the facies present in the zone (figure 1).

The continental margin is oriented from north-northwest to south-southeast, with east-west sectors, as a result of recent tectonic movements (Baldy *et al.*, 1977; Sanz de Galdeano, 1990) that have conditioned the coastal direction, as well as the location of river mouths. On the continental shelf, the

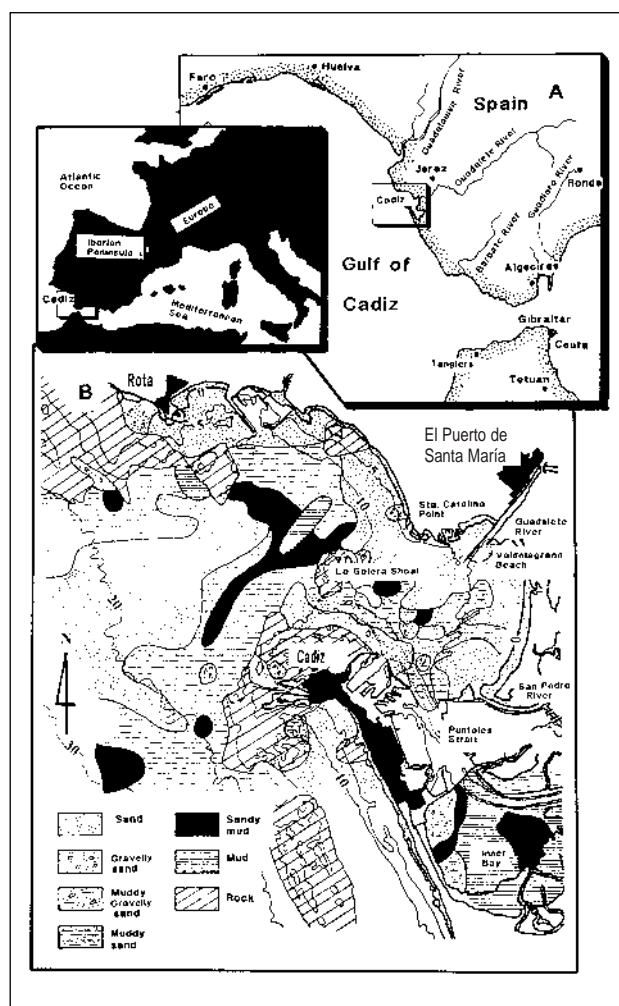


Figure 1. (A): geographic situation; (B): distribution of granulometric facies

hydrodynamic regime is controlled by the North Atlantic Surface Current (NASW), which sweeps the shelf from northwest to southeast, and by the Mediterranean Out-Flow (MOW), that pushes out over the continental slope, lying at a depth that varies from 300-1 500 m, towards the west and northwest, but without any substantial effect on the shelf itself (Heezen and Johnson, 1969; Madelian, 1970; Zenk, 1975; Ambar and Howe, 1979). The main coastal current is influenced mainly by the rough weather from the west and northwest, and flows towards the southeast; however, with an easterly wind (*Levante*), the current is observed to flow to the west, while southerly winds direct the current to the north and northwest. The tidal regime is mesotidal and semidiurnal, with a maximum amplitude of 3.7 m; given the open morphology of the coast, tidal action is only significant in appropriate physiographic zones, such as in Cadiz Bay, where it controls the transport of sediments in suspension.

Between the mouth of the Guadalquivir River and Cape Trafalgar, the continental shelf presents a shallow slope and an extension of 25 km. In Cadiz Bay, two sectors can be differentiated: an outer sector, open to the sea, and well-connected to the continental shelf, and an inner sector or *saco interior*, with lagoon characteristics and wide tidal flats with a complex system of tidal creeks. Both sectors are connected by Puntales Strait (figure 1). In the northern sector of the bay, the contributions come from the Guadalete River and other smaller rivers; in the southern sector, material is transported by the action of the tidal currents draining the inner zones of the bay, in the absence of rivers.

MATERIALS AND METHODS

Sampling was undertaken with gravity cores and Van Veen drags. A total of 300 samples were collected at 30 stations, distributed across different sectors of the bay and the adjacent continental shelf. In addition, 30 water samples were taken for the study of suspended particulate matter, in the inner and outer zones of the bay and on the continental shelf. The sampling was conducted from three boats simultaneously with the passage of the Landsat satellite over the zone, in order to obtain a synoptic picture of the turbid flumes, by comparing sample data with the satellite images.

The matter in suspension was separated out by filtering a given volume of water using pre-weighed grit filters and draining for 24 hours at 80 °C. The granulometric analysis was performed with a mechanical sieve for the coarse fraction and laser diffraction analyser for the fine fraction. Mineralogical content was determined by XRD (powder method for the total fraction and oriented aggregate (OA) for the fraction < 2 µm).

Statistical analysis of data was carried out using BMDP program; multivariate factoranalysis was used for the establishment of the mineral associations and the areal distribution of the variations between mineral associations.

RESULTS

Types of sediments

The sediments of the floor of Cadiz Bay and of the adjacent continental shelf are siliciclastic, with 25 % bioclastic carbonates (figure 1). On the continental shelf, the majority mineral is quartz, up to an average content of 80 %. There are carbonates in smaller proportions (20 %), principally calcite (Gutiérrez Mas *et al.*, 1995). Three sectors can be differentiated granulometrically: a sandy coastal zone, a prodeltaic muddy zone, related to supplies from the Guadalquivir River, and a southern zone of relict sands. The main clay minerals of the sediments are: illite, at an average content of 20 %, to a maximum of 40 %, followed by smectite (10 %), kaolinite+chlorite (8 %); and the interstratified clay mineral illite-smectite (5 %) (figure 2A,B).

In Cadiz Bay, quartz is the main component, the content varying between 85 % in sandy zones and 25 % in muddy zones. Feldspars are present in smaller quantities, less than 10 %; and phyllosilicates are found at an average content of 10 % in the outer bay and 30 % in the inner parts. The most abundant carbonate mineral is calcite, with an average content of 22 %.

In the inner bay, clayey mud is predominant, while in the outer bay and on the continental shelf, sand is predominant. Above the sand, there is a very muddy band/layer which extends from the inner bay out to the continental shelf. In the outer bay, illite predominates at contents between 50 % and 70 %, followed by smectite (10-15 %), kaolinite+chlorite (15 %) and interstratified clay mineral

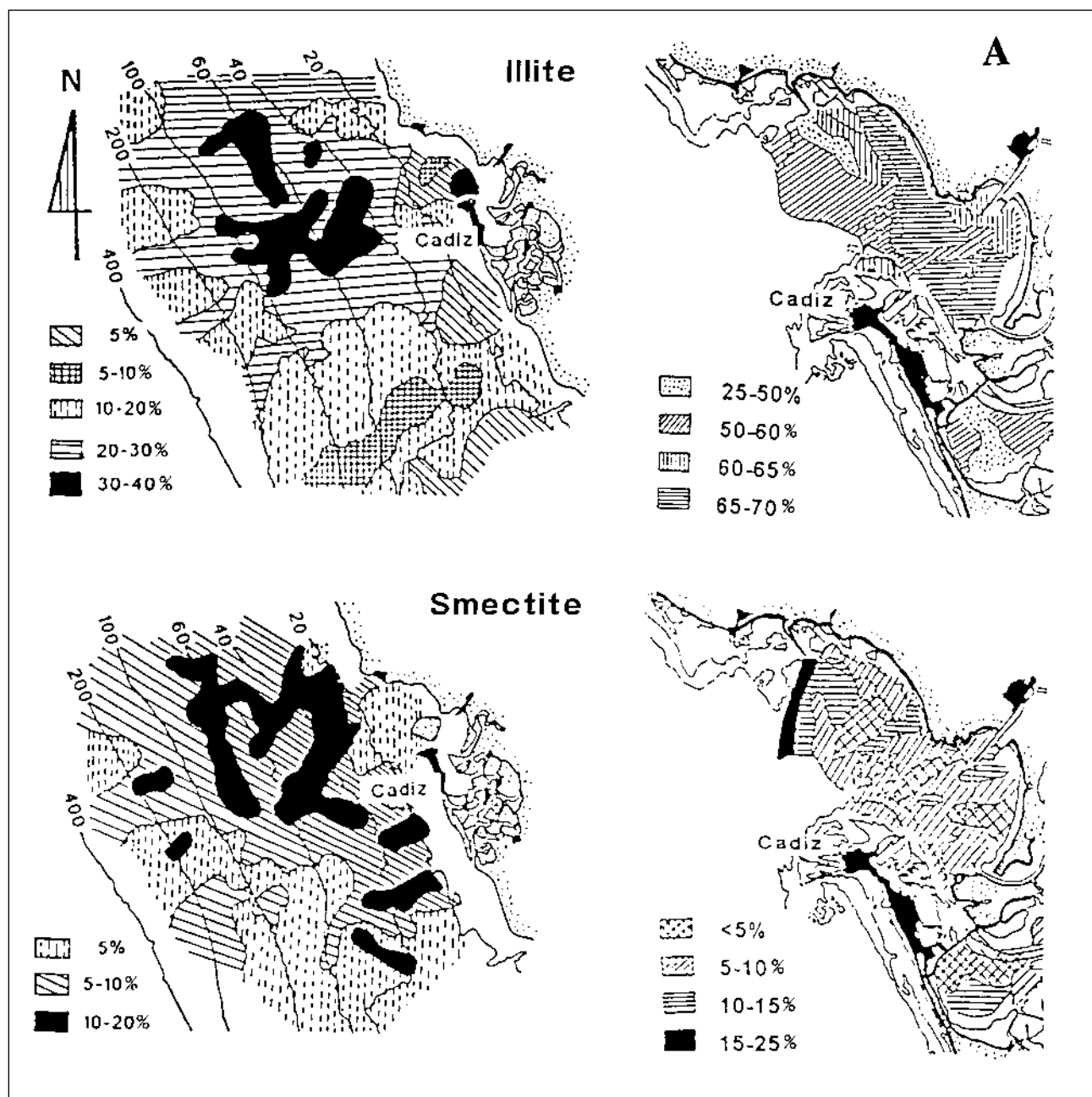


Figure 2. Distribution of clay minerals on the floor of Cadiz Bay and adjacent continental shelf. (A): illite and smectite; (B): illite-smectite and kaolinite + chlorite

illite-smectite (5 %). Illite also predominates in the inner bay, but at lower contents than in the outer part (40 %), then interstratified clay mineral illite-smectite (15-20 %), smectite (10 %) and kaolinite + chlorite (15 %) (figure 2A,B).

Measurement of suspended matter concentration, under the climatic and hydrodynamic conditions prevailing the times of the sampling, show an average dry weight content of 6.5 mg/l. The lowest values (down to 1.37 mg/l) were found at the most

distant zone from the coast and at the greatest depth, on the continental shelf itself, as well as in those sectors of the inner bay less affected by currents. The highest values (up to 14 mg/l) were found in the outer bay (figure 3), coinciding with the pattern of tidal currents and with the distribution of granulometric facies on the sea floor (figure 1).

Analysis of the mineralogical composition of suspended matter (figure 4) shows that the most abun-

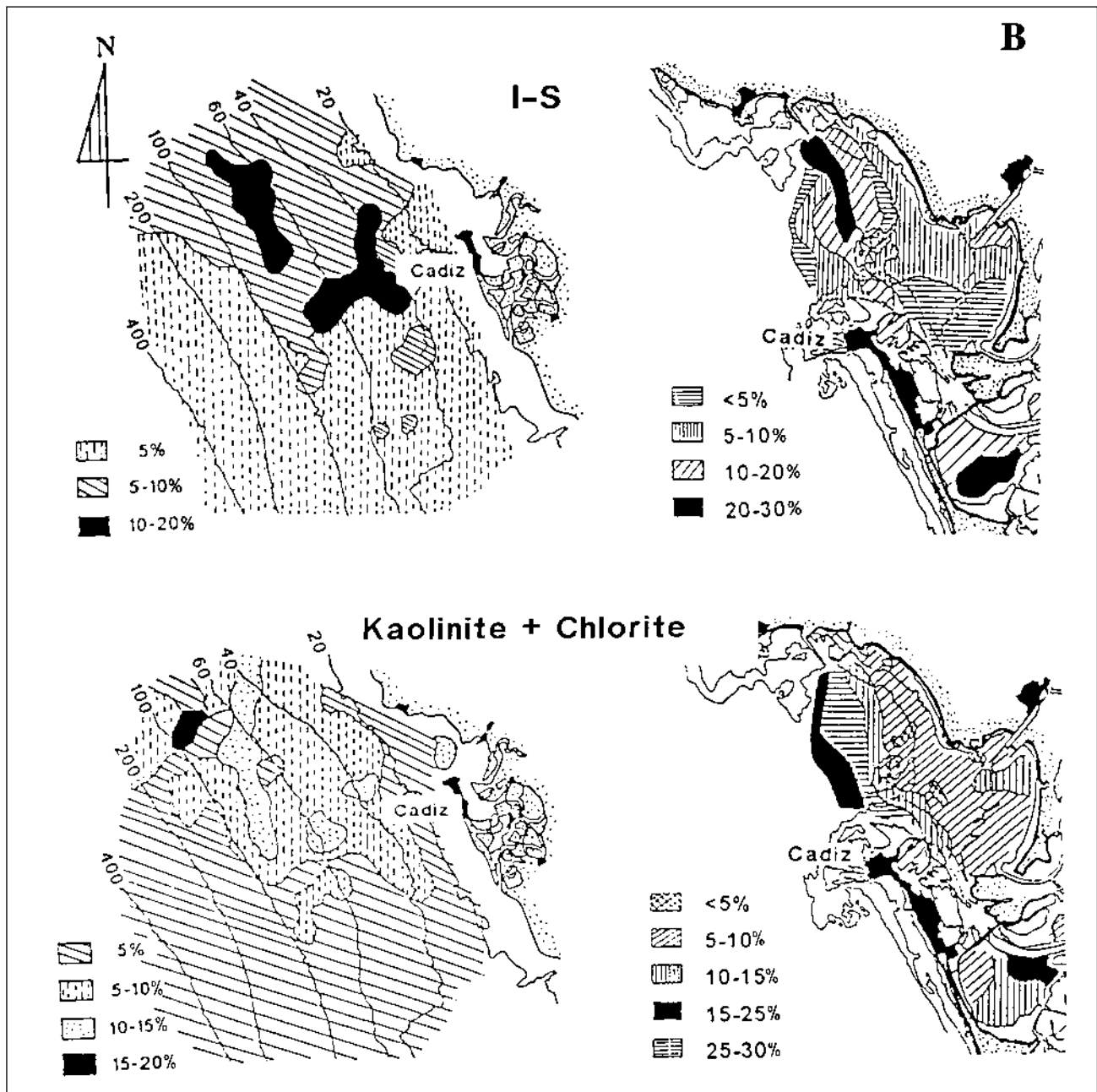


Figure 2 (continued)

dant clay minerals are illite, with an average content of 40 %, and smectite (39 %), followed by kaolinite+chlorite (15 %) and interstratified clay mineral illite-smectite (6 %). These data indicate that the standard distribution of the clay minerals is similar in all the environments sampled; it demonstrates high compositional homogeneity, only disturbed by small variations. Thus, the results permit the proposition that the continuous sedimentary exchange, resulting from the continuity and periodicity of the hy-

drodynamic processes, produces a mineralogical homogenisation of the fine sediments.

The lack of mineralogical diversity between the different environments makes it very difficult to establish the paths of sediment transport, thus making it necessary to relate the local variations of the mineralogical associations present in the sediments with those sea floor zones affected by the action of the water flows. Therefore factor analysis was applied to mineralogical composition data of the clay fraction,

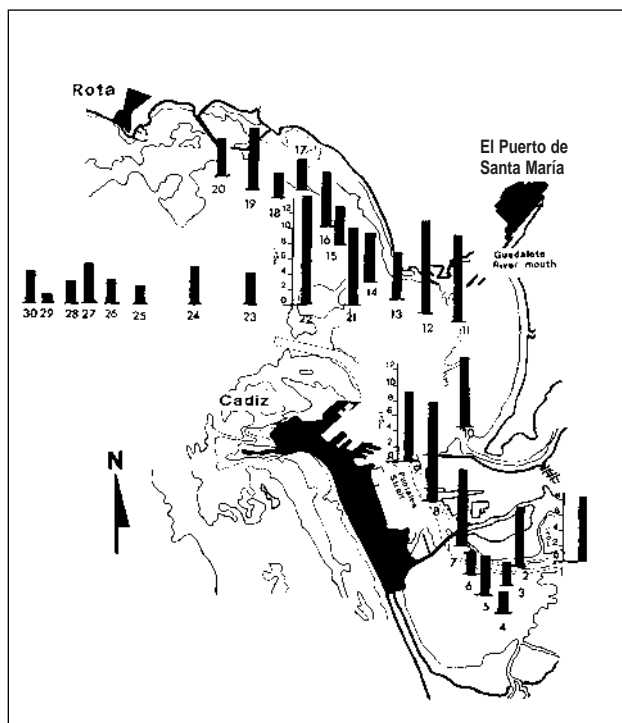


Figure 3. Suspended matter (dry weight in mg/l) in waters of the different zones of Cadiz Bay and of the adjacent continental shelf

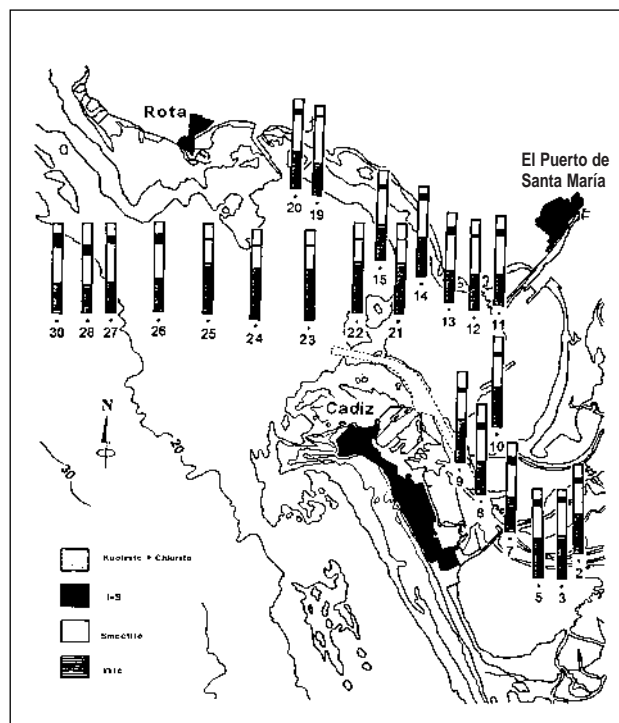


Figure 4. Clay minerals present in the particulate matter in waters of Cadiz Bay and adjacent continental shelf

and produced two factors. For the sediments of the sea floor, the first and most significant factor associates kaolinite+chlorite, smectites and illite (figure 5),

and is well represented in the inner zone of the shelf facing the mouth of Cadiz Bay. A second factor associates interstratified clay mineral illite-smectite

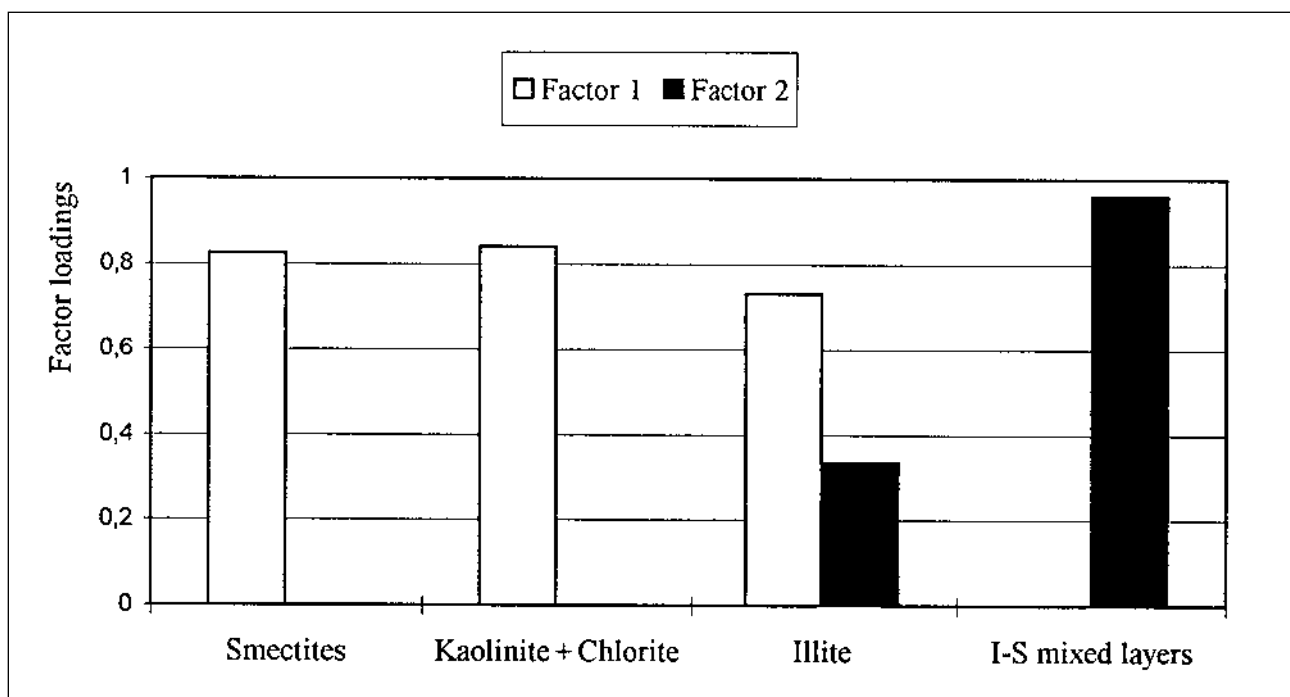


Figure 5. Bar chart of the factor loading values for each clay mineral

with illite (figure 5) and is also well represented in the inner zone of the shelf, facing the bay and the mouth of the Sancti Petri tidal creek. The predominant mineralogical association for the matter in suspension is represented by the first factor (kaolinite + chlorite, smectites and illite).

The cartographic representation of the factor scores indicate that the lower scores of the first factor are oriented in two bands extending at right angles to the coast line, running from within Cadiz Bay out to the continental shelf. The lower scores of the second factor are found in the inner shelf facing the mouth of the Sancti Petri tidal creek (figure 6).

The Landsat images were taken 3 h after high tide when the tide was ebbing, with wind from the north and northeast at an average speed of 55 km/hr, mean wave height of 0.6 m and maximum of 1.5 m. Under these conditions, the existence of water masses of different degrees of turbidity could be observed clearly (figure 7). The highest turbidity was observed in the mouths of the Sancti Petri tidal creek and the San Pedro and Guadalete Rivers. The turbid flumes appeared as large flumes of matter in suspension, oriented from the inner zone towards the outer bay extending to the continental shelf, following the morphology of the coast and the sea floor. These flumes were moved seawards by action of the tidal ebb currents, which had been in progress for 3 h at the time when the satellite image was taken.

In particular, these images show that the path of the turbid flumes coincides almost exactly with the area of the most muddy facies present on the floor of the outer bay and with the geographical locations of the sampling stations providing the highest contents of particulate matter.

Sedimentary dynamics

The mineralogical similarity observed could be the result of the homogenisation generated by the periodical action of the hydrodynamic processes, mainly controlled by the tidal ebb currents. When sediments from different source areas reach Cadiz Bay, they are subjected to homogenisation processes by the tidal flows in the inner waters of the bay. The homogenisation results from the continuous agitation of the floor through the action of tidal currents in the confines of the bay. Due to the orientation of the mouth of Cadiz Bay and to the morphology of the sea floor, the tidal ebb current is the main agent of the transport seaward and subsequent precipitation of the particulate matter on the continental shelf, when the flows reach the deeper waters.

From the mineralogical point of view, the sediment transport paths of these flows are shown by slight variations in the mineral content of the sediments. These variations do not affect the overall mineralogical composition but they do cause a decrease in the values of the factor scores at those sampling stations located where the influence of the flows is strongest. The alignments of the lowest values of the factor scores indicate the paths followed the outflows from within Cadiz Bay towards the continental shelf (figure 6).

DISCUSSION

In all the environments studied, the mineralogical similarity of the components of the clay fraction is related to the mixing and homogenising of the suspended particulate matter received from different

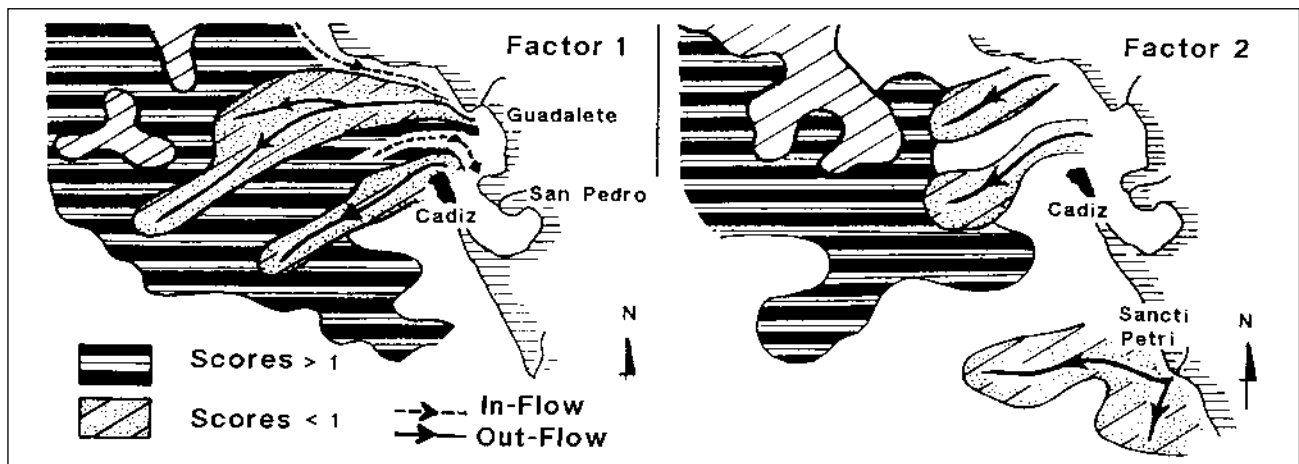


Figure 6. Representation of the factor scores at the sampling stations on the continental shelf

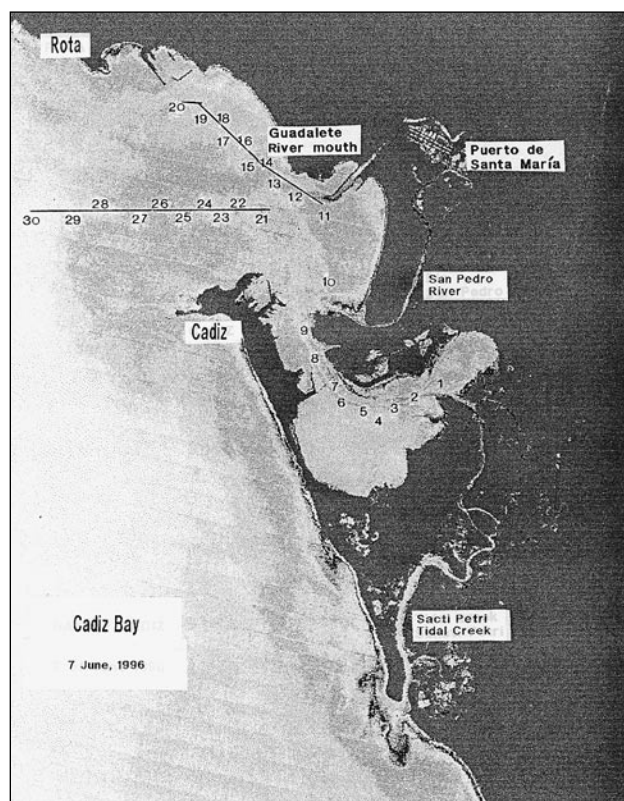


Figure 7. Landsat satellite image of Cadiz Bay showing the distribution of turbid flumes under conditions of ebbing tide (date: 06-07-1996; time: 10:30, sunny)

sources, as a result of the agitation of the muddy floor and of the continuous action of the tidal currents.

The concentration of suspended matter under the hydrodynamic conditions at the sampling time shows an average content of 6.5 mg/l. The lowest values (1.37 mg/l) were found in the continental shelf waters and the highest values (14 mg/l) in the outer bay, consistent with the pattern of tidal currents and the distribution of fine facies on the sea floor.

The Landsat images show the existence of water masses of different degrees of turbidity. The greatest turbidity is observed at the mouths of the Sancti Petri tidal creek and the San Pedro and Guadalete Rivers. The turbid flumes extend from the inner bay out to the continental shelf, following the coastline and sea bottom morphology, and are pushed by the ebb tide. The tidal ebb current is the main mechanism responsible for the transport and distribution of the fine sediments from Cadiz Bay out towards the continental shelf.

The sediment transport paths of the outflows over the continental shelf have been established by means of the local variations in the predominant

mineralogical associations and are indicated by the alignments of the lowest values of factor scores at the sampling stations.

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